Extended cut-off wavelength nBn detector utilizing InAsSb/InSb digital alloy

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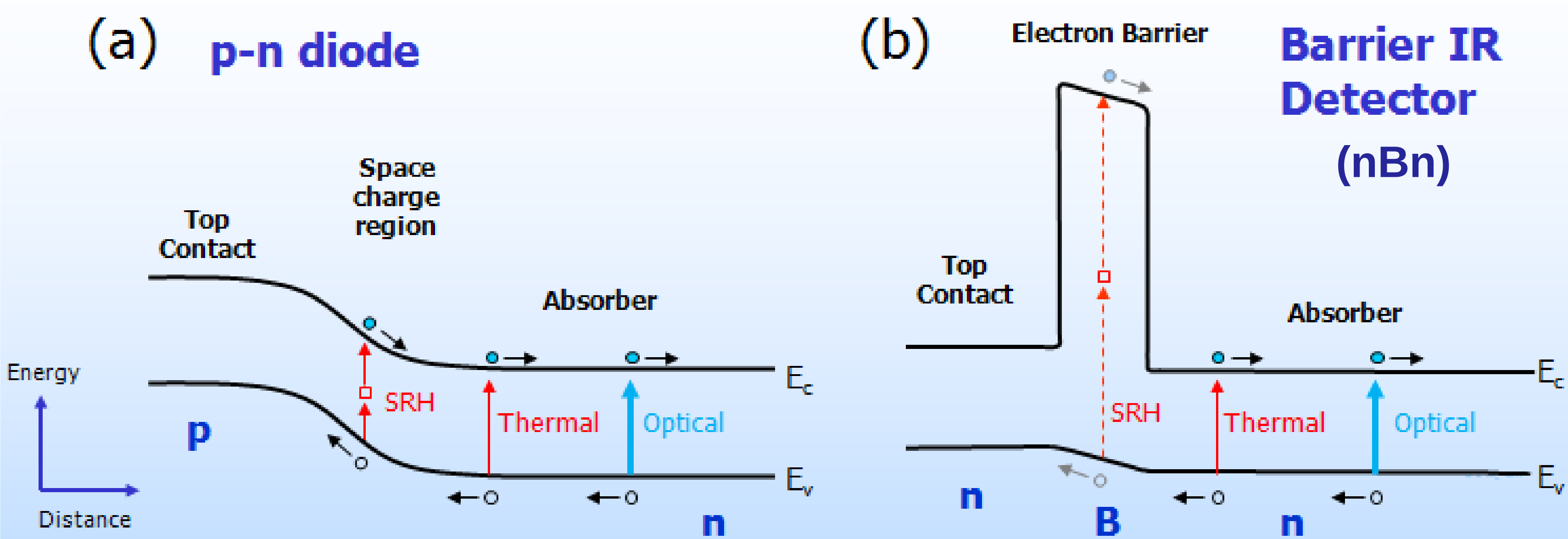
Outline

- Barrier Infrared Detector (BIRD)
  - **InAsSb nBn detector**
  - Quantum Dot Barrier Infrared detector
  - Digital alloy InAsSb/InSb Barrier Infrared detector

Barrier Infrared detectors



Barrier Infrared Detectors (BIRD)

- Different implementations: nBn, XBn, pBn, CBIRD, …
- Utilizesunipolar barriers
- Block one carrier type, but allows un-impeded flow of the other

BIRD advantages

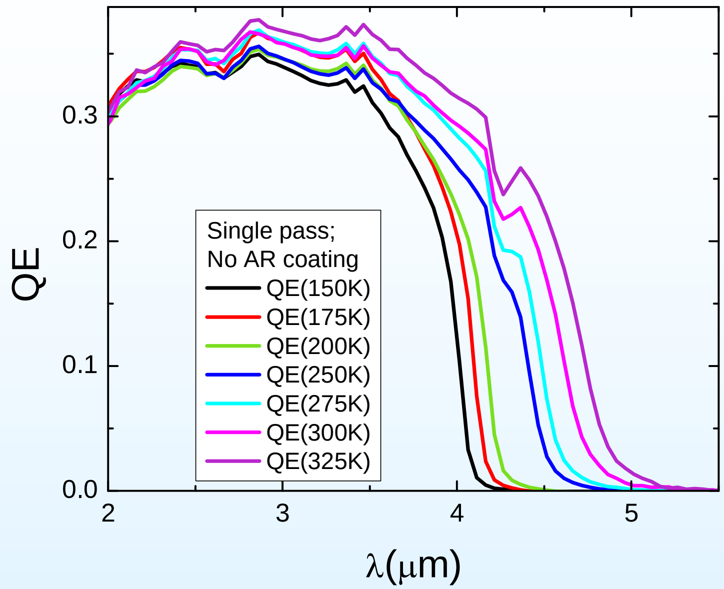
- Suppressed generation-recombination current
- Simplified fabrication process utilizing shallow etching into the barrier
- Elimination of surface leakage currents

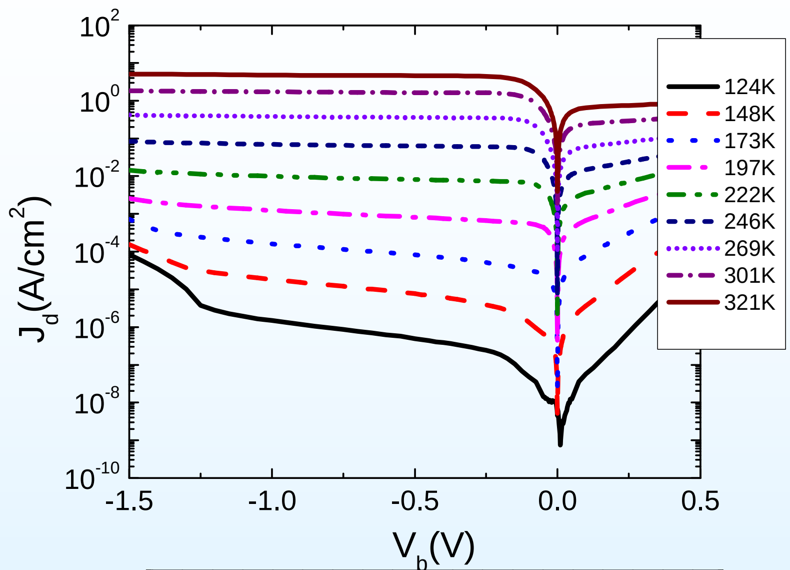
nBn utilizing an InAsSb/AlAsSb absorber-barrier combination

- Cut-off wavelengths in this design is limited to about λ_c = 4 μm

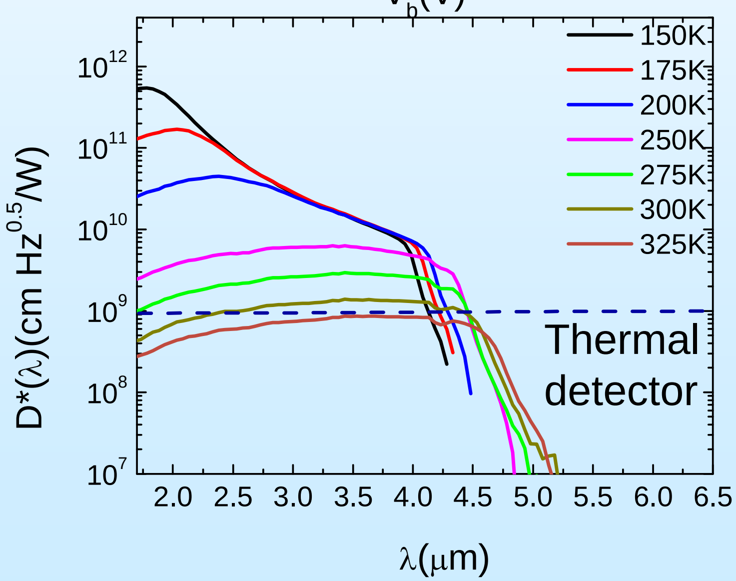
Maimon, S., and G. W. Wicks (2006). nBn detector, an infrared detector with reduced dark current and higher operating temperature. Appl. Phys. Lett. 89, 151109
Klipstein, P. (2008). 'XBn' barrier photodetectors for high sensitivity and high operating temperature infrared sensors. Proc. SPIE 6940, 69402U-2.

nBn performance at high temperature





- Very good performance up to high temperatures
  - High QE
    - λc = 3.8μm at T =77K
    - λc = 4.7μm at T =325K
  - Low dark current
    - $j_d = 7\text{x}10^{-7}$ A/cm^2 at T = 148K
    - $j_d = 6\text{x}10^{-2}$ A/cm^2 at T = 246K
  - High Detectivity
    - BLIP below 225K
    - $D^*(\lambda) = 5\text{x}10^9$ (cm Hz$^{0.5}$/W) at 250K



A. Soibel, et. al., Room temperature performance of mid-wavelength infrared InAsSb nBn detectors, Applied Physics Letters 105, 023512 (2014)

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Quantum Dot Barrier Infrared detector

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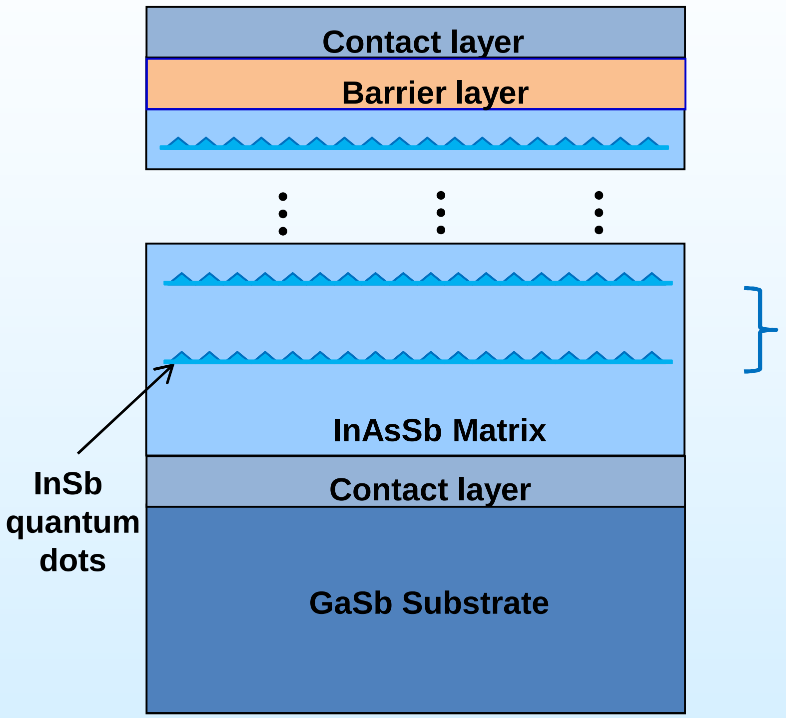
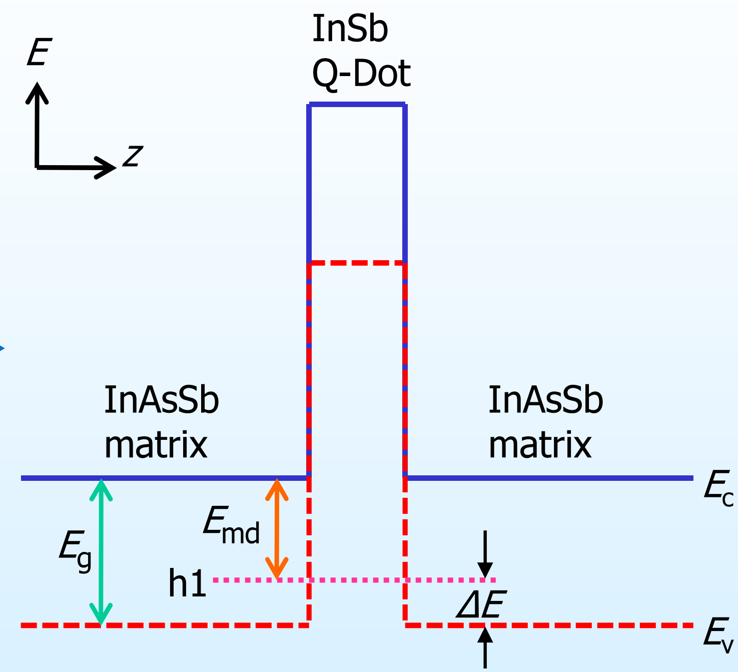
How to extend cut-off wavelength of InAsSb BIRD detector?



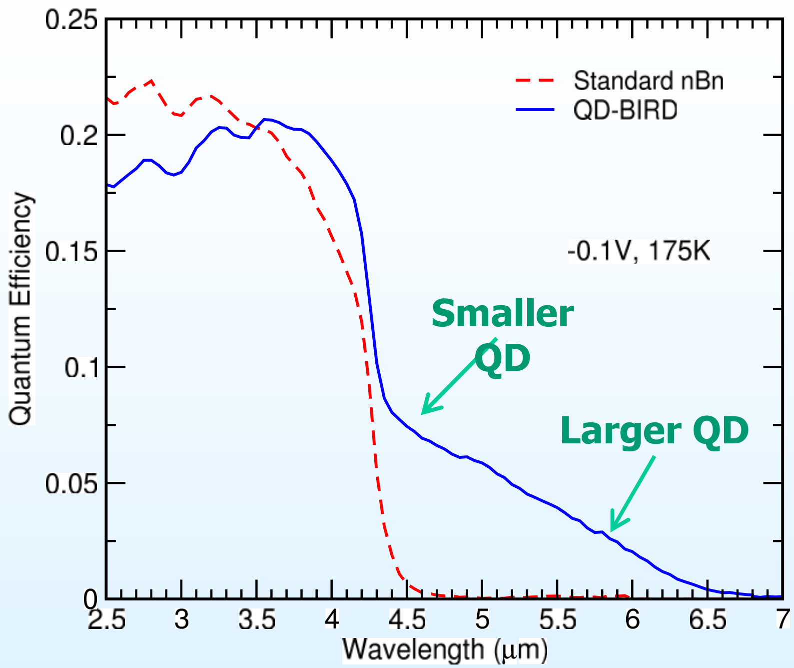


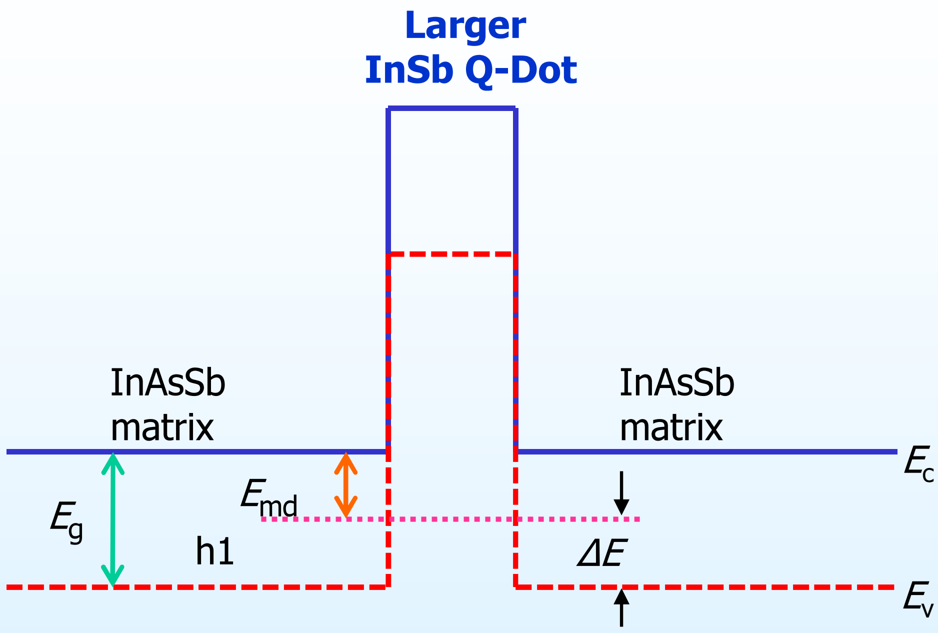
- Quantum Dot (QD) BIRD is based on a simple modification of the standard nBn
- Periodic insertion of InSb quantum dot layers

- Type-II broken-gap band alignment between InSb and InAsSb
- InSb QD conduction band state is in the continuum (unconfined)
- InSb QD valence band state can be confined in the gap of InAsSb matrix

C.J. Hill, *et. al*., Mid-infrared quantum dot barrier photodetectors with extended cutoff wavelengths, Electronics letters. 46, 1286 (2010).

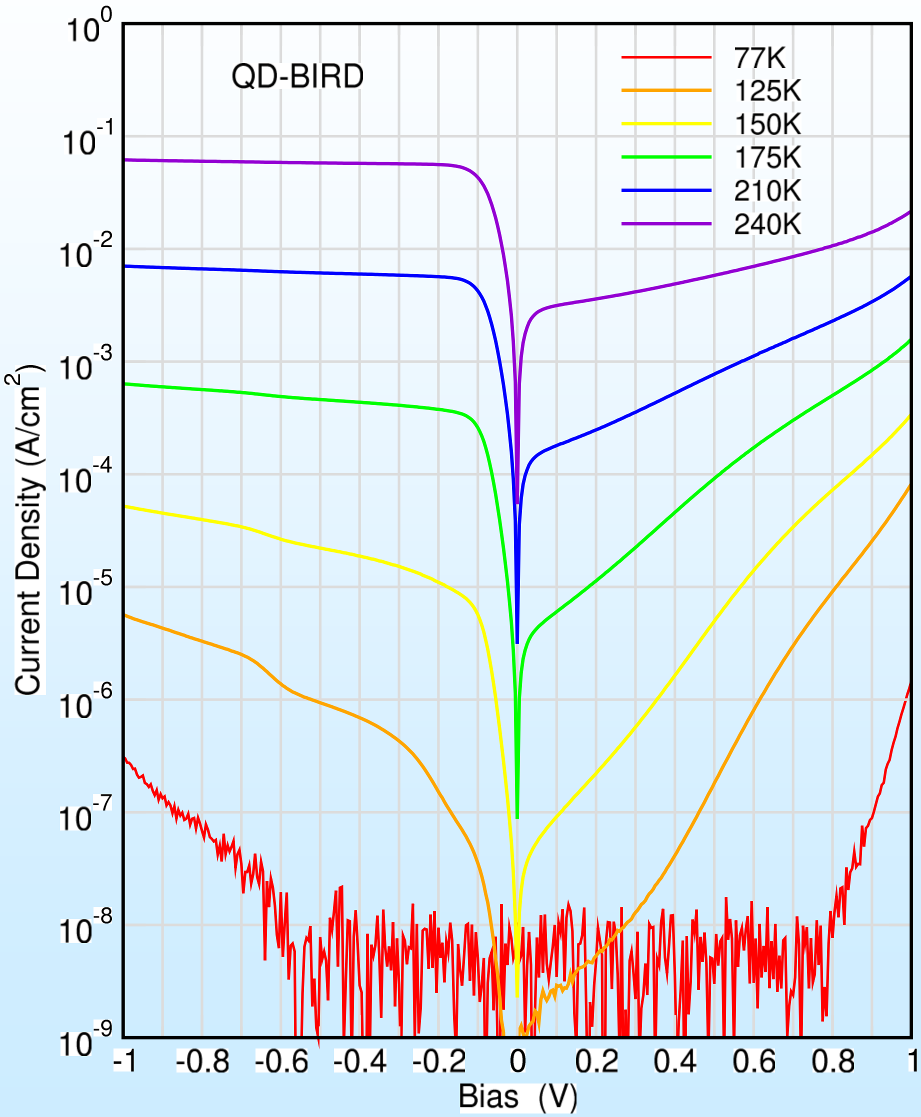
Photo-Response and Dot Size Distribution





- <u>Bimodal</u> behavior found for spectral response as in PL spectrum
- Extended response out to ~6μm
  - Weaker than InAsSb bulk response
  - QE decreases with wavelength
    - Attributed to Quantum Dot size distribution
  - Large QDs have
    - Smaller transition energy E_{md} , longer absorption wavelength
    - Larger activation energy ΔE , lower hole escape probability, reduced photo-response

Dark Current Density and D*



- Higher temperature reverse-bias I-V appears diffusion limited
- Lower temperature I-V shows exponential increase
  - Fowler-Nordheim barrier
- Reasonably low dark current
  - J(-0.2V, 175K)= 3.77×10^{-4} A/cm^2
  - J(-0.2V, 125K)= 1.52×10^{-7} A/cm^2
- Black-body D*
  - f/2, 300K background
  - Use integrated photo-response from 3 μm to 6 μm
  - D*(-0.2V, 175K)=1.07×10^{11} cm-Hz$^{1/2}$/W
    - Dark current limited
  - D*(-0.2V, 125K)=3.76×10^{12} cm-Hz$^{1/2}$/W
    - Background limited

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Digital alloy Barrier Infrared detectors

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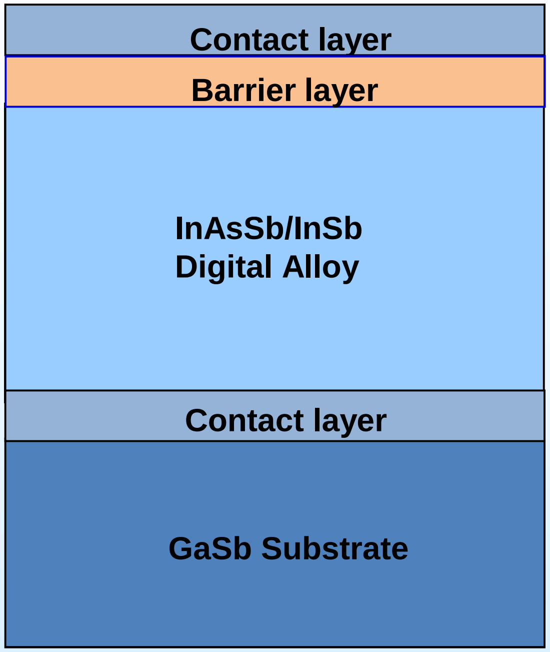
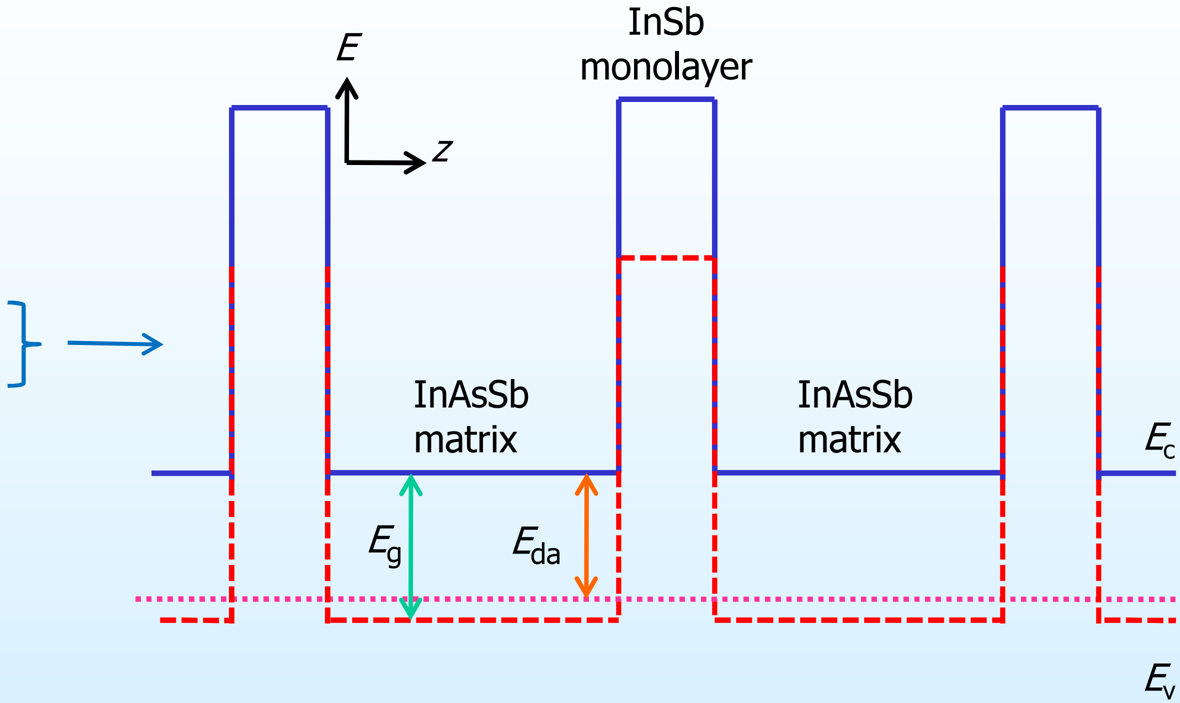
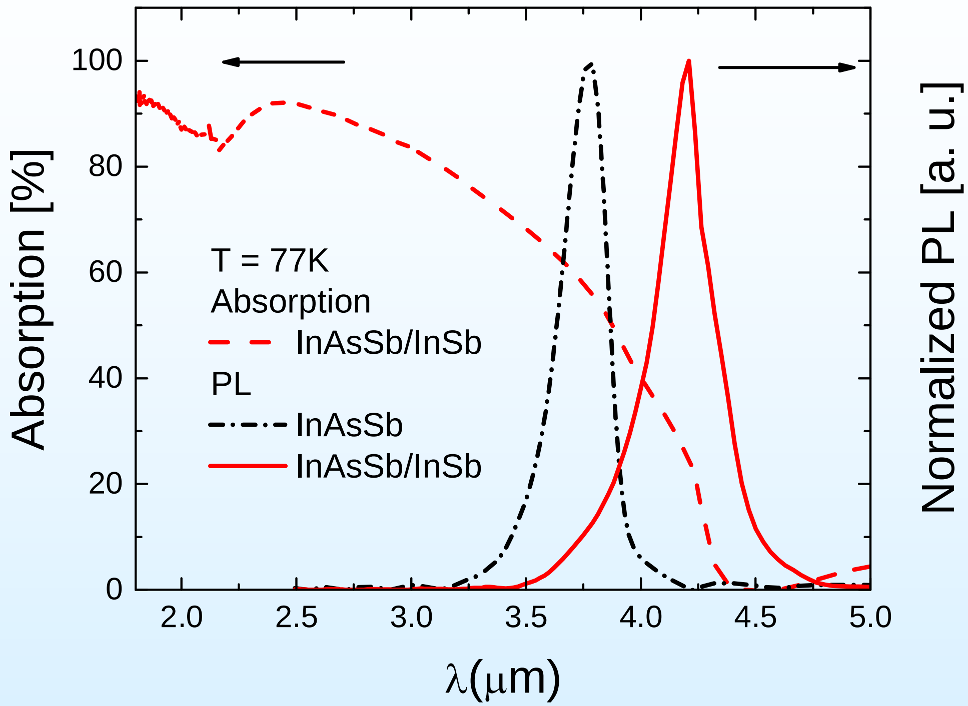




- Digital alloy InAsSb/InSb is based on a simple modification of the standard nBn
- Periodic insertion of InSb monolayers
  - A single InSb monolayer after every 14 monolayers of $InAs_{0.92}Sb_{0.08}$
- Type-II broken-gap band alignment between InSb and InAsSb
- New level with transition energy, E_{da}
  - Transition energy $E_{da} < E_g$, where E_g is InAsSb bandgap

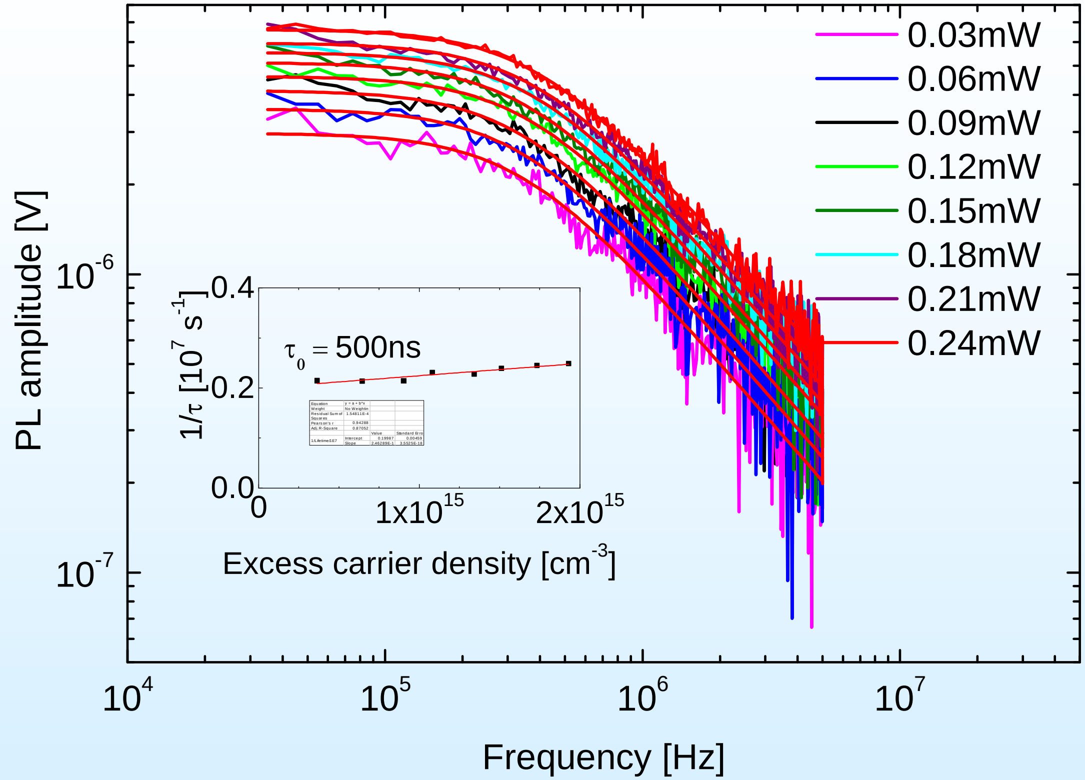
A. Soibel *et. al.*, Mid-wavelength infrared InAsSb/InSb nBn detector with extended cut-off wavelength, Applied Physics Letters 109, 103505 (2016)

PL and absorption



- At T = 77K, the digital alloy exhibits PL peak = 4.21µm
  - Compared to the = 3.79µm of $InAs_{0.915}Sb_{0.085}$ bulk material
  - Compared to the = 5.5µm of InSb QD embedded in $InAs_{0.915}Sb_{0.085}$ bulk material
- The absorption spectrum of the 2µm thick digital alloy absorber is shown above
  - Absorption is a = 70% and the absorption coefficient is a_c = 2900 cm^{-1} at λ = 3.4 µm
- The transmission of the GaSb substrate used for the growth of these devices was found to be higher than >95% for λ < 6µm

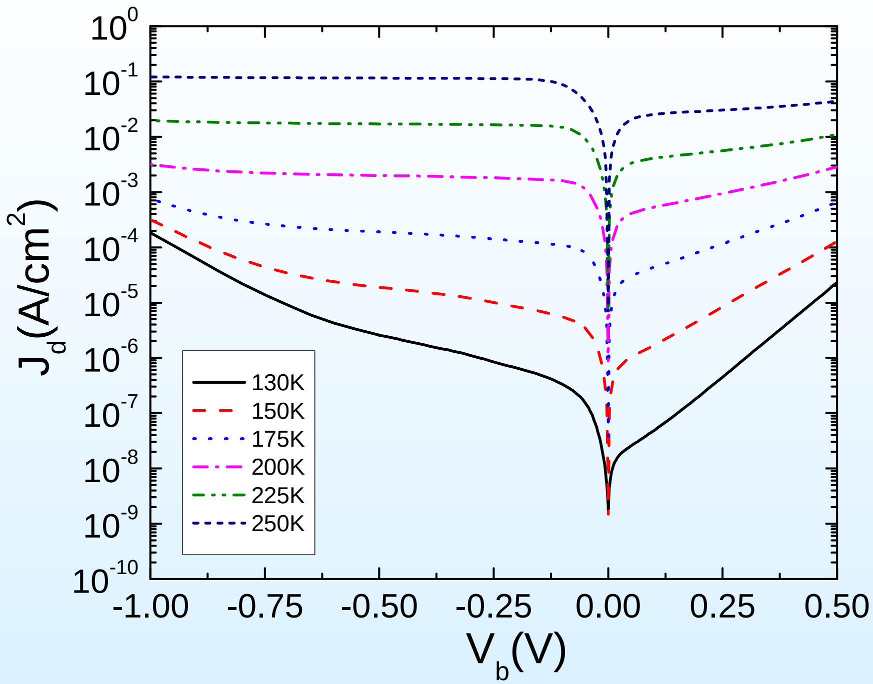
Lifetime



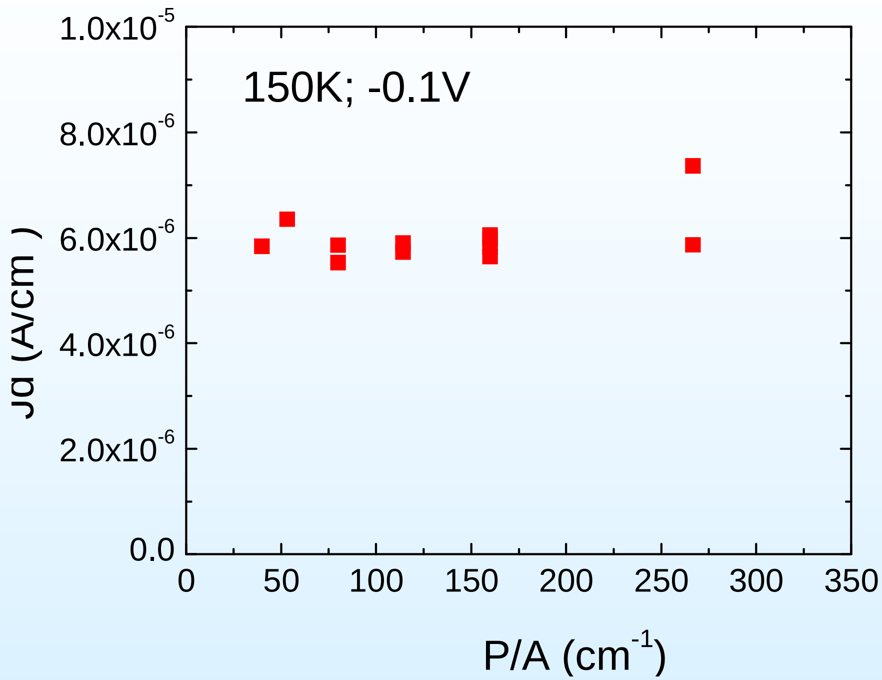
- The minority carrier lifetime in the digital alloy, τ_{da} = 500 ns, at T = 77 K
- The estimated radiative recombination time τ_r = 470-570 ns
    - From the absorption spectrum and the carrier concentration, n_{abs} = 3-4$\times$$10^{14}$ cm^{-3}
    - Close to the experimentally measured lifetime
    - Radiative recombination controls the minority carrier lifetime at T = 77 K
- The minority carrier lifetime in $InAs_{0.915}Sb_{0.085}$ bulk material τ_{bulk} = 300 ns
    - For carrier concentration of n = 1-2 x10^{15} cm^{-3}

Dark current

Dark current density vs. applied bias at different T

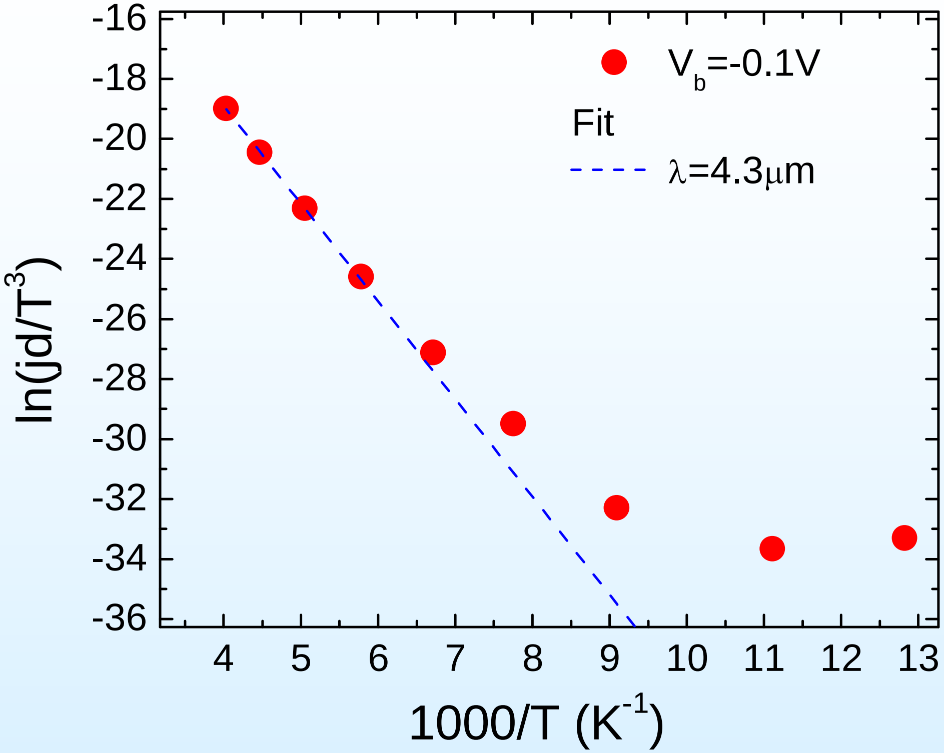


Dark current vs. perimeter/area ratio



- Shallow etched devices - etching just below the barrier
- The dark current density
  - $j_d = 5 \times 10^{-6}$ A/cm^2 at $V_b = -0.1$ V and $T = 150$ K
  - $j_d = 2 \times 10^{-3}$ A/cm^2 at $T = 200$ K
- The dark current vs. perimeter/area ratio is flat
  - No the surface leakage current
  - No the lateral current collection due to a partial pixel delineation
  - Indicative of a large ratio of pixel size to lateral diffusion length

Arrhenius analysis



- Dark current fit (the dashed line): $j_d \sim T^3 \exp(-E_G/k_B T)$
  - E^f_G = 4.3μm found from the fit to the data
  - Close to the superlattice bandgap E_G = 4.2μm
- Dark current is diffusion limited at low bias and temperatures above 150K
-The activation energy decrease at temperatures below 150K
  - Generation-recombination (g-r) and tunneling currents starts to dominate

Capacitance-Voltage measurements

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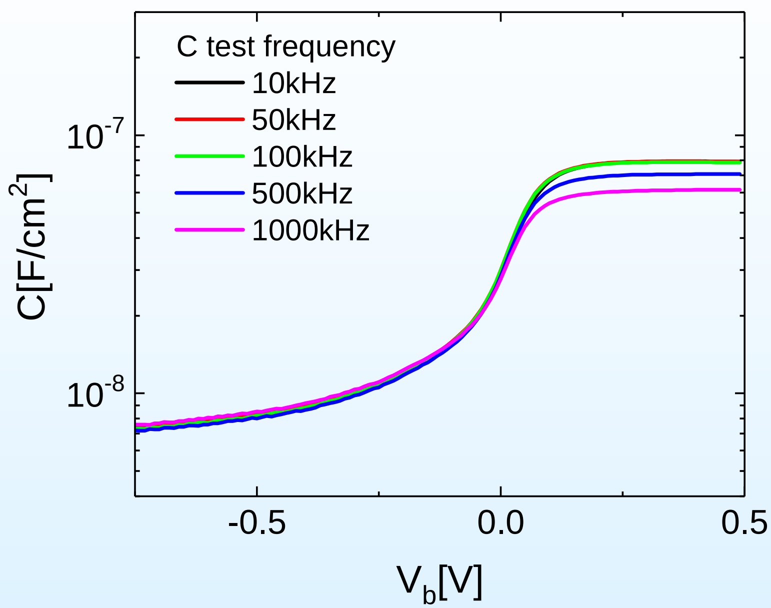
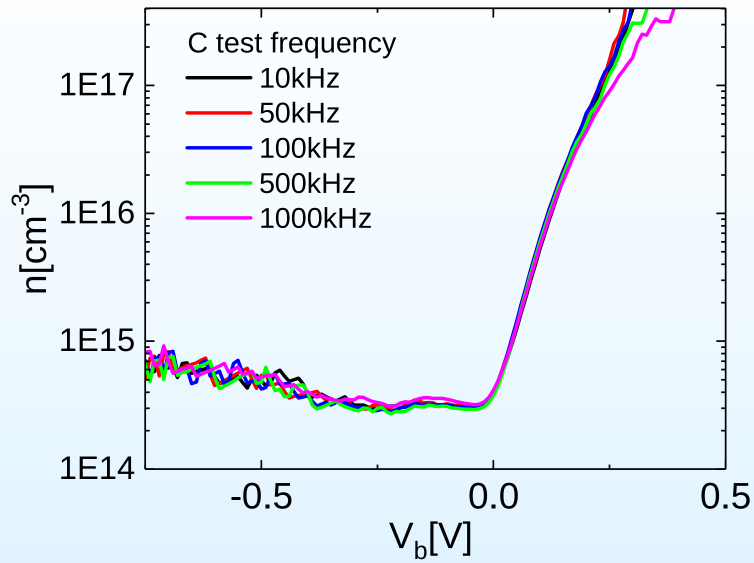




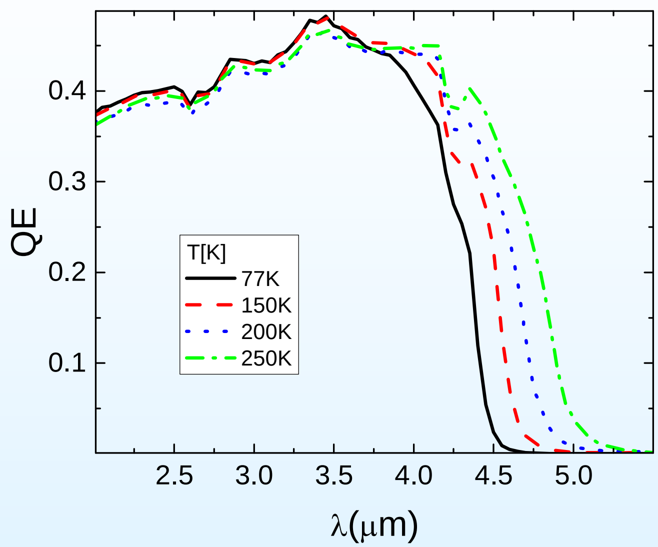
- Capacitance vs. voltage (C-V) was measured at T=77K

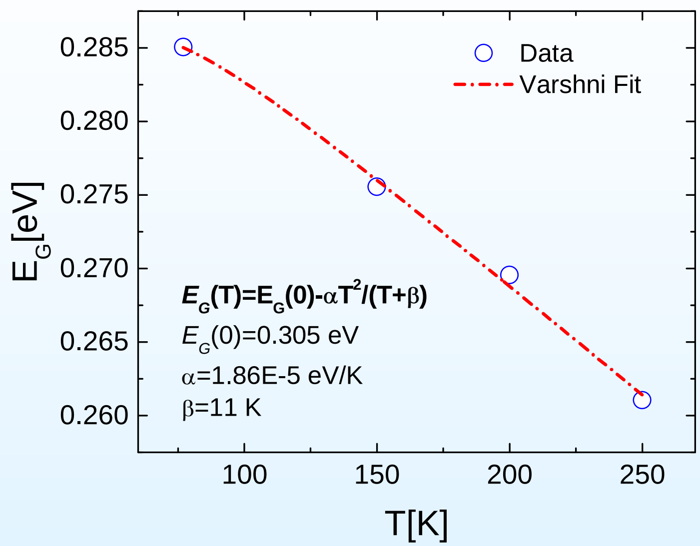
- Carrier concentration was calculated from C-V data using expression for diodes

  - $n_{abs} = 3\text{-}4\times10^{14}$ cm^{-3}

$$\boxed{n = -\frac{2}{q\varepsilon_0\varepsilon_s A^2 \dfrac{d}{dV}\left(\dfrac{1}{C^2}\right)} = \frac{2}{q\varepsilon_0\varepsilon_s \dfrac{d}{dV}\left(\dfrac{1}{(C/A)^2}\right)}}$$

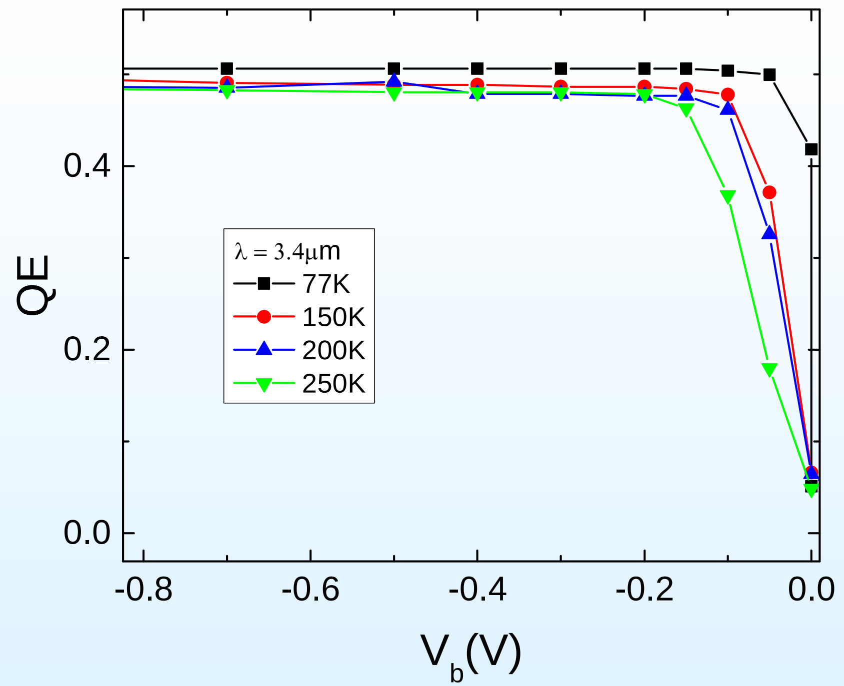
Spectral response





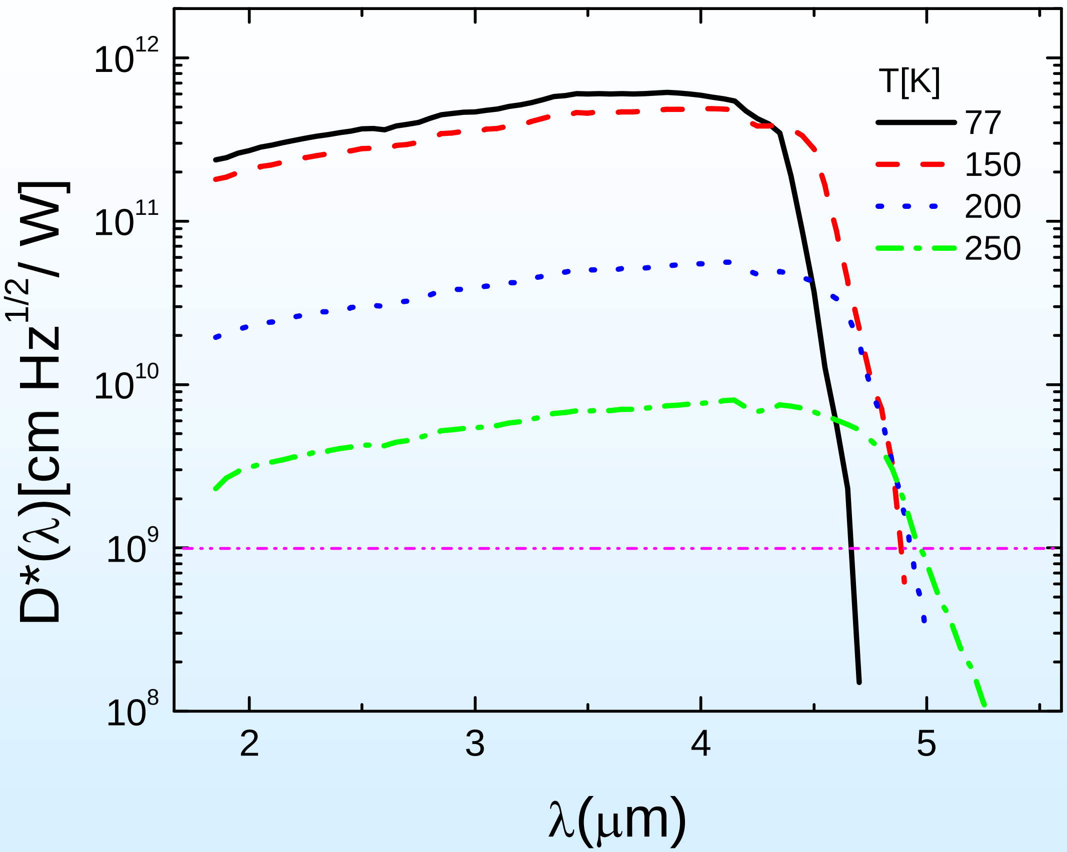
- Spectral response of backside-illuminated detectors without antireflection coating
    - The transmission of the GaSb substrate >95% for $\lambda < 6\mu m$
    - Double pass response
- The cut-off wavelengths, λ_c changes with temperature
    - λ_c = 4.34 μm at T = 77 K
    - λ_c = 4.77 μm at T = 250 K
- Fit bandgap change with temperature using Varshni expression

Temperature dependence of QE_{resp}



- The maximum Quantum Efficiency is $QE^{max} \approx 0.5$
  - Does not change with temperature in the temperature range T = 77 – 250 K.
- QE estimation from absorption: $QE_{est} = (1-R)(\alpha + \alpha(1-\alpha))$
  - α is a single-pass absorption and R = 0.34 is the reflectance of GaSb substrate
  - $QE_{est} \approx 0.6$ at $\lambda = 3.4$ mm is very close to the measured $QE^m \approx 0.5$
- Turn-on bias, V_{on}, is less than 50 mV at T = 77 K
  - Indicates good valence band alignment between the barrier and absorber
  - Turn-on bias increases with temperature to about V_{on} = 150 mV at T = 250 K
  - Turn-on bias increase can be attributed to band-bending effects

Detectivity D*



Thermal detector

- Detectivity, $D^*(\lambda)$ is for background T300K, *f*/2 field of view and 3 – 5 µm window
- Detectors are background limited at T = 150 K and below
    - $D^*(\lambda)$ = 3 - 6x10^{11} cm $Hz^{0.5}$/W
- $D^*(\lambda)$ = 2 - 4x10^{10} cm $Hz^{0.5}$/W at T = 200 K

Summary

We extended the cut-off wavelength λ_c of bulk InAsSb nBn detectors to λ_c = 4.6 μm at T = 200 K by incorporating series of single InSb monolayer into InAsSb absorber

- Detectors with 2μm thick absorber showed a temperature independent quantum efficiency $QE^m \approx 0.5$ for back-side illumination without antireflection coating.

- The dark current density was $j_d = 5 \times 10^{-6}$ A/cm^2 at T = 150K, and increased to $j_d = 2 \times 10^{-3}$ A/cm^2 at T = 200 K.

- At temperatures of T = 150 K and below, the demonstrated photodetectors operate in background limited performance (BLIP) mode, with detectivity $D^*(\lambda)$ = 3-6x10^{11} cm Hz$^{0.5}$/W for the background temperature of 300 K, and f/2 field of view.